U S D A FOREST SERVICE
RESEARCH NOTE RM-210

FOREST SERVICE
U.S. DEPARTMENT OF AGRICULTURE

ROCKY MOUNTAIN FOREST AND RANGE EXPERIMENT STATION

Throughfall and Stemflow Relationships in Second-Growth Ponderosa Pine in the Black Hills

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In linear regression, gross rainfall alone accounted for 85 percent to as high as 99 percent of throughfall variation at individual gage points. Stemflow was also primarily dependent on gross rainfall. Results further demonstrate adjustment of throughfall for mean canopy density, adjustment of stemflow for tree size (d.b.h.), and combination of these relationships to estimate net rainfall for different stand densities.

Keywords: Watershed management, hydrology, Pinus ponderosa.

Variabilities of throughfall and stemflow have been variously attributed to random error (Stout and McMahon 1961), tree parameters, or characteristics of the forest canopy. In their extensive review of interception studies in mature hardwoods, Helvey and Patric (1965a) concluded there is no consistent evidence that interception losses are greatly affected by a variety of canopy densities. They go on to say, however, that failure to show variations in throughfall has probably been due more to failure of sampling methods to adequately measure variation than to lack of variation itself. They further maintain that throughfall under mature hardwoods must be inversely proportional to canopy density. The same logic must also apply to conifers.

Stout and McMahon (1961) conclude that amount of throughfall under a specific tree may vary with position or direction of the sampling point from the trunk. Their findings agree in general with earlier works reported by Beall (1934), Ovington (1954), and Geiger (1957). Such variations have been attributed to density of foliage immediately above the gage (Horton 1919). Most such conclusions, though logical, are not well supported, and, as pointed out by Helvey and Patric (1965a), do not adequately define relationships of an interlaced forest canopy, especially where there is more than one canopy level.

Stemflow is, as a rule, more variable than throughfall. Helvey and Patric (1965b) attribute this greater variability to the endless variety of branch arrangements and bark roughness between trees. In some studies there have been no strong correlations of several tree dimensions with stemflow (Black 1957). In a number of other studies summarized by Helvey and Patric (1965a), stemflow has been definitely associated with such factors as bark roughness, trunk diameter, and height of crown above the general canopy level. Lawson (1967) concluded that addition of a tree size variable greatly improved stemflow predictions for both pines and hardwoods.

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Opportunity for further analysis of the influence of canopy and tree variables on throughfall and stemflow was provided by measurements taken in connection with a study of soil moisture trends after clearcutting and thinning in a second-growth ponderosa pine stand in the Black Hills (Orr 1968). The accumulating evidence that interception reduces transpiration to some degree (Rutter 1968) makes it even more important that the throughfall and stemflow processes be understood and accounted for in hydrologic analyses.

Study Area

Throughfall was measured on three 30- by 30-foot subplots each in a 120- by 150-foot thinned plot and in an adjacent unthinned plot in second-growth ponderosa pine about 70 years old. The thinned stand had 435 trees per acre averaging 36 feet tall and 5.8 inches diameter, breast high (d.b.h.). The adjacent unthinned stand contained 2,885 trees per acre averaging 29 feet tall and 3.5 inches d.b.h.

Stemflow was measured on all 10 trees on one 30- by 30-foot thinned subplot, and on a random sample of 10 out of 54 trees on one 30- by 30-foot unthinned subplot.

The plots were on the lower and more gently sloping (9 percent) portion of a steep north- to northeast-facing slope. Soils appeared to have developed in place from limestone parent material. Site index is between 70 and 75, near maximum for ponderosa pine in the Black Hills. Precipitation averaged 21.3 inches per year over a 5-year period. Precipitation usually is minimum during the winter, builds to a maximum in June, and declines gradually through the summer and fall.

Methods

Throughfall was measured with two standard 8-inch cans rotated about a system of 10 random points on each of the three subplots in each of the two treatments. Hence, 30 points were sampled in each treatment. Measurements were taken yearlong at minimum 1-week

Two standard 8-inch cans were rotated about a system of 10 random points on each of three subplots in each of two treatments to measure throughfall.

intervals for 3 years. Occasional in-between measurements were taken in case of large storms. Gages were weighed and contents converted to inches depth. The two gages on each subplot were moved to another pair of points after any measurement period in which gross precipitation equaled or exceeded 0.05 inch. Because gages were located at only two of 10 sampling points per subplot at any given time, there are five different sets of precipitation data, each representing a different set of six gage points.

Stemflow was collected in copper collars attached to the trees and sealed with plastic cement. Collar openings were about one-half inch. The water was piped to 6-gallon containers and weighed for each tree. Stemflow was measured for 2 years.

Gross precipitation was measured with both a recording and standard gage in a nearby forest opening with minimum 45° clearance, and in one standard gage near the center of a 120- by 150-foot clearcut plot adjacent to the thinned and unthinned plots. Oil was used in all gages to minimize evaporation.

Canopy was photographed from ground level at each of the 30 throughfall gage points in each of the two treatments, with the hemispherical camera described by Brown (1962). Percentage canopy was estimated in each of 80 equal hemisphere segments from zenith to 90°. Values were averaged for an assortment of zenith and azimuth segments. Estimates were made by two different individuals and repeated by one individual after several months had elapsed. There was practically no difference in estimates between individuals or between repeat estimates by the same individual.

Tree measurements, including d.b.h., height to live crown, total height, and crown diameter were made by standard mensurational techniques.

Only the summer rainfall data (May-September, 1958-60 inclusive) were analyzed in detail. Winter and spring data were complicated by occasional mixed rain and snow, and by recording difficulties.

The principal throughfall analyses involved stepwise regression of throughfall on rainfall variables for each gage point, followed by regression of mean throughfall at individual points on canopy density. The precipitation variables tested in the initial analyses were gross rainfall, number of storms per observation interval, and an expression of rainfall intensity. In the final analysis, all 30 sampling points in each treatment and the two treatments were combined.

Stemflow analyses involved regression of stemflow on rainfall variables for individual sample trees, introduction of tree variables, and final combination of all sample trees in the two treatments.

Assumptions of linearity were checked. Results did not justify an attempt to fit curves in either the throughfall or stemflow analyses.

Results

Throughfall

Rain throughfall was more variable in the unthinned than in the thinned stand. Mean canopy density in full azimuth, 52° zenith projection, ranged from 28 to 48 percent and averaged 42 percent in the thinned stand, and ranged from 52 to 75 percent and averaged 66 percent in the unthinned. Part of the greater throughfall variability in the unthinned stand was obviously due to greater magnitude of sampled drip concentration there. At one point, for example, where measured canopy density was 70 percent, the recorded throughfall was two to three times greater than gross rainfall, but only for gross rainfall amounts exceeding about 2 inches. Similar results have been reported by other investigators (Ovington 1954, Wicht 1941).

In all of the 30 individual sampling-point regressions in each of the two treatments, gross rainfall alone accounted for 92.9 to 99.7 percent of throughfall variation in the thinned stand and from 85.5 to 99.7 percent in the unthinned. Number of observations per gage point ranged from 8 to 12. The rainfall intensity variable was also highly correlated with throughfall at 24 to 30 points in both the thinned and unthinned stands, and the number of storms per observation interval (3-hour separation) was significantly correlated with throughfall at more than half the sampling points in both treatments. However, neither of these variables accounted for significant throughfall variation after gross rainfall in either treatment. Canopy density did not account for a consistently significant proportion of throughfall variation for different storm observation groups in the separate treatments. The range of canopy density was apparently too narrow. When the two treatments were combined, however, the range was broadened sufficiently for valid expression of the effect of canopy on throughfall.

The final regressions of throughfall (Y_1) on gross rainfall (X_1) alone were:

Thinned

$$Y_1 = -0.004 + 0.888X_1 \qquad (R^2 = 0.96) \; [1]$$

Unthinned

$$Y_1 = -0.054 + 0.813X_1 \qquad (R^2 = 0.82) \; [2]$$

Combined regression for thinned and unthinned, incorporating the 52° zenith projection full azimuth canopy density variable [X_2] expressed in percent yielded the following equation:

$$Y_2 = 0.167 + 0.851X_1 - 0.0037X_2 \; (R^2 = 0.89) \; [3]$$

Throughfall estimates from separate equation [1] and [2] are compared with estimates for both treatments obtained with equation [3] (table 1). Equation [3] estimates mean throughfall from the mean of gross rainfall with adjustment for canopy density.

Mean canopy densities for other zenith projections and in the azimuth range of prevailing winds were computed, but those tested were interrelated to so high a degree that no single one was significantly better than another. This does not mean that closer relationships or better expressions of canopy density do not exist. A more efficient sampling scheme specifically designed for the purpose will be necessary to establish such relationships. Nevertheless, the present study clearly demonstrates use of canopy density parameters to quantitatively account for a portion of throughfall variation.

Stemflow

All completely recorded amounts of gross rainfall larger than 0.2 inch yielded measurable stemflow from at least one gaged tree in one or the other of the two treatments. The final analysis involved 21 summer rainfall events larger than 0.2 inch in both of the treatments over the 2 years of measurement.

Table 1.--Regression estimates of mean throughfall using equations 1, 2, and 3

	Item	Observation group[1]				
		1	2	3	4	5
$\overline{X}_1$	Mean observed gross rainfall (inches)	0.680	0.430	0.751	0.866	0.743
$\overline{X}_2$	Observed mean canopy density (percent) 52° zenith projection, full azimuth					
	Thinned stand	41.8	41.8	41.0	40.3	43.3
	Unthinned stand	67.3	64.2	66.3	69.0	61.8
$\overline{Y}$	Mean observed throughfall (inches)					
	Thinned stand	.59	.41	.66	.77	.63
	Unthinned stand	.47	.31	.54	.58	.64
Y_1	Estimated mean throughfall (inches)					
	Thinned stand (Eq. 1)	.60	.38	.66	.77	.66
	Unthinned stand (Eq. 2)	.50	.30	.56	.65	.55
Y_2	Estimated mean throughfall (inches) from mean gross rainfall with adjustment for canopy density (Eq. 3)					
	Thinned stand	.59	.38	.65	.75	.64
	Unthinned stand	.50	.30	.56	.65	.57

[1] Each group represents a set of six gages, each set having a different group of rainfall events due to gage rotation.

Here, as in the case of throughfall, gross rainfall was the only significant precipitation variable in combined regressions. The combination equations for regression of pounds of stemflow (Y) on gross rainfall (X_1) for all 10 trees in each of the two treatments are:

Thinned

$$Y = -1.94 + 13.21X_1 \qquad (R^2 = 0.57) \qquad [4]$$

Unthinned

$$Y = -2.43 + 13.09X_1 \qquad (R^2 = 0.31) \qquad [5]$$

$$X_1 \geq 0.2 \text{ inch}$$

The addition of tree variables greatly improved on these regressions. All three variables tested—d.b.h., tree height, and crown volume (taken as volume of cylinder whose diameter = mean crown diameter)—were significantly correlated with stemflow, but height and crown volume were not significant after d.b.h. because of high intercorrelation. R^2 values increased to 0.66 and 0.50 for thinned and unthinned stands, respectively, after including d.b.h. D.b.h. appears to be more important in the unthinned stand, considering the greater increase in R^2.

The regression equation after combining the two treatments and incorporating d.b.h. (X_2) is:

$$Y = -21.18 + 13.10X_1 + 4.49X_2 \quad (R^2 = 0.55) \qquad [6]$$

$$X_1 \geq 0.2 \text{ inch}$$

Estimated equivalent areal depth would be equal to estimated pounds for the average size tree on a given sample area, times the number of trees, converted to volume and divided by land area. Size of trees involved in this study ranged from 2.9 to 6.6 inches d.b.h.

Throughfall and Stemflow Combined (Net Rainfall)

Addition of throughfall and stemflow yields net rainfall, here defined as depth of rainfall reaching the surface of the forest floor. In the study area there was virtually no understory vegetation—just a bare mat of pine needles at the forest floor surface. Combination of equations [3] and [6] yielded the following equation for net rainfall:

$$\begin{aligned} Y = {} & n_1 (0.167 + 0.851\overline{X}_1 - 0.0037\overline{X}_2) \qquad [7] \\ & + n_2 N(-0.0000936 + 0.00005783\overline{X}_3 \\ & + 0.00001986\overline{X}_4) \end{aligned}$$

where

- Y = Net rainfall (inches)
- n_1 = Number of recorded precipitation events $\geq$ 0.05 inch
- $\overline{X}_1$ = Average depth (inches) of all precipitation events $\geq$ 0.05 inch
- $\overline{X}_2$ = Average canopy density (percent)
- n_2 = Number of recorded precipitation events $\geq$ 0.20 inch
- $\overline{X}_3$ = Average depth (inches) of rainfall events $\geq$ 0.20 inch
- $\overline{X}_4$ = Average d.b.h. (inches) of all trees on sampled area
- N = Number of trees per acre

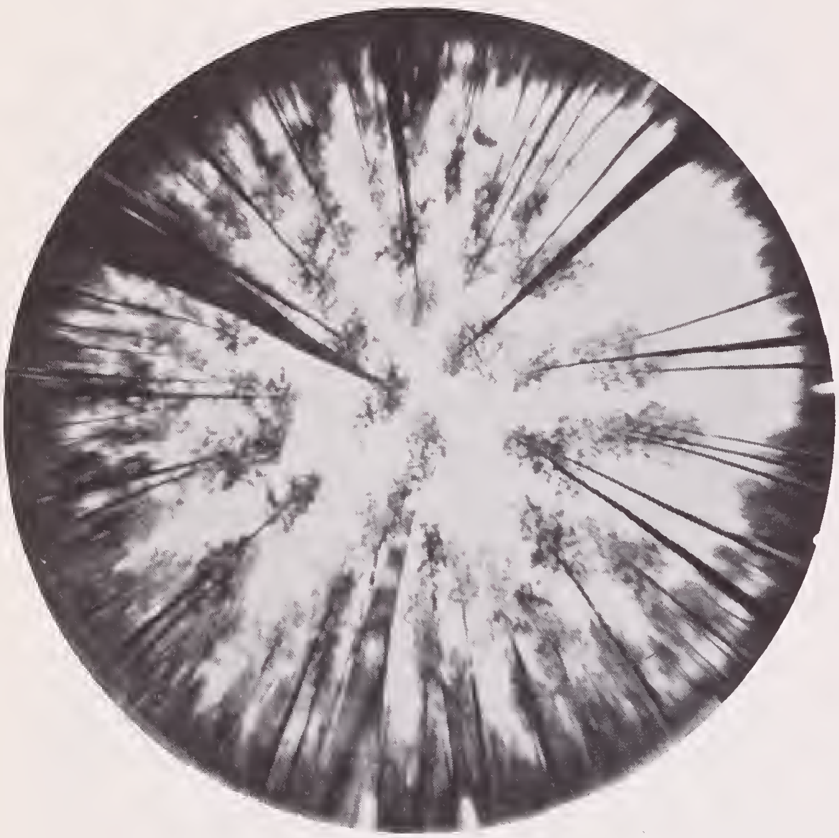
The first part of the equation provides an estimate of throughfall adjusted for canopy density, and the second part an estimate of pounds of stemflow converted to inches depth according to tree d.b.h. and number of trees per acre. This relationship is based on and hence is strictly applicable to a rather narrow situation—one forest type, one age class, and one climatic regime—in which only precipitation amounts equal to or larger than 0.05 inch were considered.

However, considering the surprising similarity of results from studies of different species at widely separated locations, it seems likely that the equation may yield realistic estimates of the relative magnitude of net rainfall (or interception loss) over a much larger area. For such use the exact method of determining canopy density probably is not critical so long as it is consistent.

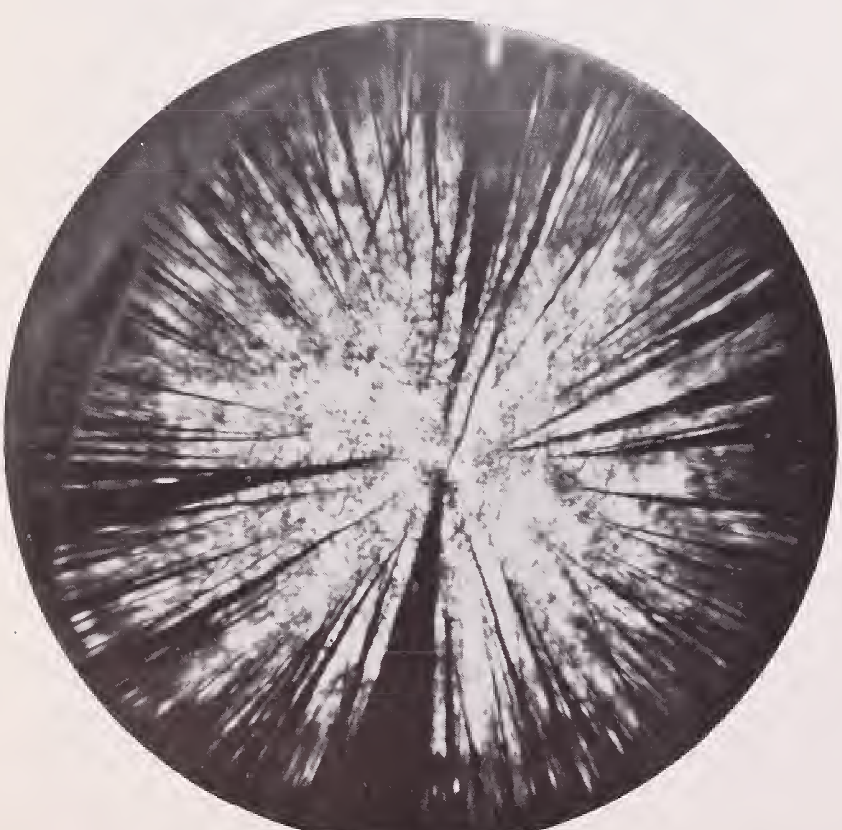
Summary and Discussion

This study demonstrates a possible method of estimating net rainfall in relation to stand density of second-growth ponderosa pine in the Black Hills. As in virtually all reported studies in both conifer and deciduous forest types, gross precipitation depth is the primary

Canopy was photographed from ground level at each of 30 throughfall gage points in each of two treatments, with a hemispherical camera (Brown 1962):



This thinned stand has 435 trees per acre (N), averaging 5.8 inches d.b.h. ($\bar{X}_4$). Canopy density ($\bar{X}_2$) is about 41 percent (in 52^{o} zenith projection). Consider a single storm of 0.75 inch ($n_1 = 1$, $n_2 = 1$, $\bar{X}_1 = 0.75$, $\bar{X}_3 = 0.75$). Applying equation [7], throughfall is calculated as 0.65 inch and stemflow 0.03 inch, for a total net rainfall of 0.68 inch, or 91 percent of the amount of rainfall reaching the ground in the open.



This unthinned stand has 2,885 trees per acre (N), averaging 3.5 inches d.b.h. ($\bar{X}_4$). Canopy density ($\bar{X}_2$) is about 66 percent (in 52^{o} zenith projection). Consider a single storm of 0.75 inch ($n_1 = 1$, $n_2 = 1$, $\bar{X}_1 = 0.75$, $\bar{X}_3 = 0.75$). Applying equation [7], throughfall is calculated as 0.56 inch and stemflow 0.06 inch, for a total net rainfall of 0.62 inch, or 83 percent of rainfall reaching the ground in the open.

controlling variable in both throughfall and stemflow. This primary control is clearly obvious in studies that have involved regression analyses. However, a combination of results from adjacent thinned and unthinned plots accounted for an additional small but nevertheless significant proportion of both throughfall and stemflow variances. This provided the basis for adjusting throughfall for percent canopy density and adjusting stemflow for tree d.b.h. The combination of these two relationships yields an equation for net rainfall.

Canopy density is the most obvious factor that it would be expected might influence throughfall. However, other researchers, as pointed out earlier, have concluded that there is no consistent evidence that interception losses are greatly affected by a variety of canopy densities. The overpowering influence of gross precipitation in the ordinary regression approach is very likely one of the main reasons for this lack of consistency. In the present study, using stepwise regression, canopy density also was not significant until results from adjacent thinned and unthinned plots were combined. The combination resulted in a broad enough range of canopy density to define a significant relationship.

A variety of canopy measurements involving average percent density in different zenith projections and/or azimuth segments were tested. Densities were estimated from vertical photos taken from the ground upward at each of the throughfall points, 60 in all. Because of intercorrelation and small residual variance after gross rainfall, no one canopy variable tested significantly better than another. On a rational basis the average density in 52° zenith projection, full azimuth, was used in final analysis.

Similar tendencies were evident in stemflow regression analyses. A variety of tree size variables were tested, including d.b.h., total height, and crown volume. Each correlated with stemflow independently, but in stepwise regression neither height nor crown volume were significant after d.b.h. because of intercorrelation.

The foregoing indicates statistically definable relationships of canopy density with throughfall and tree size with stemflow. Where or when more detailed information is needed for solution of specific hydrologic problems, other sampling design and analysis techniques may yield better defined relationships. In the meantime, entry of appropriate stand measurements in the combined equation [7] will yield a realistic idea of the magnitude of net rainfall (or interception) in relation to stand density of second–growth ponderosa pine.

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